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Space Sciences Laboratory
University of California
Berkeley, California 94720

SOLAR SYSTEM MAGNETIC FIELDS AND PLASMAS

by
John M. Wilcox

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John M. Wilcox

Space Sciences Laboratory

University of California

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Solar System Magnetic Fields and Plasmas*

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This discussion will begin with the magnetic fields observed on the surface of the sun, move out to interplanetary fields and plasmas and their relation to these solar magnetic fields, and finally come to earth in a plasma physics laboratory. Against this background we discuss some recent results obtained in collaboration with N. F. Ness with the magnetometer experiment on the IMP-1 satellite as supplemented with observations obtained in collaboration with R. Howard with the Mount Wilson Observatory solar magnetograph. In particular three research problems of current interest are identified and discussed.

Solar Magnetic Fields

The strong magnetic fields associated with sunspots are perhaps the most familiar feature of the sun's magnetic field. Spots often appear on the surface of the sun in pairs as shown in Figure 1. The preceding spot (in the sense of the solar rotation) is usually somewhat nearer the equator than is the following spot. A process that has been called magnetic bouyancy by Parker[1] may be involved in the appearance of sunspots. If we consider the

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pressure balance in a tube of magnetic flux below the surface of the sun, the pressure outside of the tube is supplied only by the plasma whereas inside the tube there are two terms--the magnetic field pressure $B^2/8\pi$ plus the pressure of the plasma within the flux tube. If the temperature is approximately constant then the mass density within the flux tube will be less than in the surrounding material and the flux tube will begin to rise. Analysis indicates that the process is self-reinforcing so that the tube will continue to rise until it reaches the surface of the photosphere.

Although the details about the formation of sunspots are not well known, it is an observational fact that spots do appear as shown in Figure 1. The magnetic field within the spot itself is several hundred gauss. Each spot is surrounded by a larger region having the same sense of field as the spot itself. A large spot will increase in size and field strength for several days after which it will begin its decline. Usually after one solar rotation the spots have disappeared, but the surrounding Bipolar Magnetic Region can still be observed. In the course of several solar rotations this Region becomes weak and diffuse. There is a tendency for the following portion of a Bipolar Magnetic Region to move poleward and for the preceding portion to move toward the equator. It appears that the observed dipole-like field in the polar regions of the sun is primarily a surface effect, and is formed by the following portions of many Bipolar Magnetic Regions that have drifted poleward. In a given solar hemisphere during a given 11 year sunspot cycle the preceding spot will have one sense and the following spot will have the opposite sense of magnetic field. In the opposite hemisphere at the same time the polarity conditions are just reversed. The preceding portions of bipolar regions drift toward the equator and appear to merge together and disappear. The following portions of several bipolar regions may combine to form a large area having predominantly one polarity of field, and this has been called by Babcock and Babcock[2] a Unipolar Magnetic Region. An example is shown in Figure 1. Thus we have a picture[3] of fields that are continually moving on the surface of the sun with appreciable changes occurring in a few days in the case of sunspots, and in a few solar rotations in the case of the large scale fields.

The time for magnetic field lines to diffuse into the solar plasma is extremely long. The magnetic field can be said to be frozen into the solar plasma. In the case of field lines running through the interior of the sun the magnetic diffusion time would be comparable to the age of the sun so that in shorter times one would not expect to find appreciable motions of the field. Thus the observed rapid motions of the field would seem to be associated with plasma motions in the photosphere which drag the field lines about. Leighton[4] has suggested a random walk process whereby tubes of magnetic flux may move on the sun. Alfvén[5] has suggested that in addition to the observed surface fields there should be a general (i.e. deep lying) solar magnetic field that would not change its sense in any measurable time. Such a field has not yet been observed.

In order to give a more quantitative discussion of the large-scale solar magnetic field directions the following technique is employed. A heliographic latitude is selected and a thin strip centered at the given latitude is considered. This strip is then divided in longitude by an amount corresponding to the rotation of the sun in 12 hours. Each such area is assigned a plus sign if the field within is predominantly out of the sun, and is assigned a negative sign if the field within is predominantly into the sun. Occasional ambigious cases are omitted. An example centered at 5° south of the solar equator is shown in Figure 1. The process of course can be repeated at other heliographic latitudes. We then have produced a time series describing the large scale sense of the solar magnetic field at a given latitude.

The above discussion is based on observations made with the solar magnetograph[6] at Mount Wilson Observatory. This instrument utilizes the longitudinal Zeeman effect so that the line-of-sight component of the photospheric magnetic field is measured. The sensitivity is about 1 gauss and the angular resolution is about 23 seconds of arc, which is 1/80 of the solar diameter. The sun is scanned from one pole to the other in a raster pattern, the entire process taking about one hour. Such a solar magnetogram is obtained every day at Mount Wilson, weather permitting, and from these daily magnetograms it is possible to prepare a synoptic chart. A portion of such a synoptic chart of the photospheric magnetic field is shown in Figure 2. The solid contours represent field directed out of the sun, and the dashed contours represent field into the sun. On the left hand side of Figure 2 there is a large region with field directed out of the sun that extends considerably on each side of the equator. On the right hand side of Figure 2 is a similar region extending on both sides of the equator with field directed into the sun. Thus we can note that the large scale weak fields on the sun that are the final result of the processes discussed above can extend across the equator without noticeable changes. On the other hand, the sunspots are very much related to the equator. If a spot group forms only 2 or 3 degrees north of the equator it will almost invariably have the polarity relations appropriate to the northern hemisphere at that time, and similarly for the southern hemisphere. It seems that the sense of the magnetic field that appears in sunspots is rather strictly related to the position with regard to the solar equator, whereas the plasma motions that eventually diffuse the flux can readily move it across the solar equator.

Interplanetary Plasmas and Fields

We now move out into the interplanetary medium near the earth and consider observations obtained with the magnetometer experiment of Ness et al.[7] on the IMP-1 satellite. This satellite was launched into a highly elliptic orbit on November 27, 1963 and observed the interplanetary medium for 3 solar rotations thereafter. Apogee was at about 31 earth radii, which it well beyond the influence of the geomagentic field on the sunward hemisphere. Vector measurements of the interplanetary field were obtained with fluxgate magnetometers every 20 seconds with an uncertainty of $\pm 1/4\ \gamma$ ($1\ \gamma = 10^{-5}$ gauss).

What might we expect to find with these observations? In a series of papers published in the late 1950s Parker[8] has discussed the hydrodynamic expansion of the solar corona which results in what he calls the solar wind. Neugebauer and Snyder[9] with an experiment on the Mariner 2 spacecraft have confirmed that the solar wind plasma is always flowing in a direction approximately radially away from the sun with a density of 5 protons/cc and a velocity of several hundred km/sec. The temperature is estimated in the range of 10^5 degrees. A magnetic field with an average magnitude of about $5\ \gamma$ is frozen into the solar wind plasma. This field on the average is in the form of an Archimedes spiral[10] which is caused by the combination of the radial flow of the solar wind plasma and the solar rotation. Near the earth the angle between the spiral magnetic field and the earth-sun line is approximately 45°, because the radial velocity of the solar wind is approximately equal to the azimuthal velocity of a radius vector from the sun to the earth.

The left hand portion of Figure 3 shows the observed[10] distribution of directions of the interplanetary magnetic field component parallel to the ecliptic. The distribution is considerably peaked in directions approximately

45° away from the earth-sun line, as predicted by the spiral theory. The right hand portion of Figure 3 shows the distribution of directions perpendicular to the ecliptic plane. The most important point to note is that the field is predominantly parallel to the ecliptic and not transverse to it. However there is a predominant southward component of the field which when averaged over the 3 solar rotations observed by IMP-1 amounts to approximately 1γ . This leads us to the first of the current research problems which we wish to identify. Since this southward component is in a direction transverse to the radial plasma flow of the solar wind, the frozen-in magnetic flux is being transported along with the plasma. The product of the magnitude $B_{\perp}$ of the field component normal to the ecliptic and the magnitude of the solar wind velocity V_s gives the transport of the north-south component of the magnetic flux being observed by the satellite at each moment. The satellite observes at only a single point in space, of course, but in the course of 27 days the complete pattern will rotate past the satellite as the sun completes one rotation. (The corotation of the interplanetary magnetic field with the sun is discussed in a later section of this paper.) Each of the three solar rotations observed by IMP-1 displayed a net transport of southward directed magnetic flux of approximately the same magnitude. Therefore it seems reasonable to assume that the average transport of southward magnetic flux beyond a circle of radius one astronomical unit (centered at the sun and in the ecliptic plane) at a given instant would be approximately equal to the average transport of southward directed magnetic flux observed by IMP-1 during a complete solar rotation. The product $B_{\perp} \cdot V_s$ has an average magnitude of about 350γ km/sec (or gauss cm/sec) with the field in the southward direction. The total transport of southward flux beyond one astonomical unit in the ecliptic plane can be obtained (under the above assumption) by multiplying by the circumference of a circle with a radius of one astronomical unit. With what quantity of magnetic flux should this rate of flux transport by compared? The total magnetic flux observed[3] in the polar regions of the sun is about 10^{22} gauss cm^2, and this is also the approximate magnitude of the flux in a large Unipolar Magnetic Region.[3] The surprising result is that this amount of flux is transported beyond one astronomical unit in a few days. Thus to put the matter rather crudely the sun is "emptied" of magnetic flux in only a few days.

The average value of the southward-directed interplanetary field is about 1γ, which is larger than the stated uncertainty of the measurements $\pm 1/4\,\gamma$ but is still a rather small quantity. Careful attention has been directed to the possibility of a spacecraft field influencing this result with negative results at the present time. Observations from other satellites would also be desirable. The first paper[11] from the Mariner 4 spacecraft has reported a net southward field on Mariner 4 and also on Mariner 2.

Extension of the Photospheric Magnetic Field into Interplanetary Space

We now wish to develop a description of the sense of the interplanetary field as a function of time for comparison with the description of the sense of the photospheric magnetic field discussed above and illustrated in Figure 1. For this purpose the range in angles labeled "positive" in Figure 3 is considered to represent an interplanetary field directed predominantly away from the sun and the range of angles labeled "negative" is considered to represent an interplanetary field directed predominantly towards the sun. During most of the 12 hour periods the interplanetary field is entirely confined to one of these two conditions. Thus a time series describing the sense of the interplanetary field in 12 hour periods is produced. A cross-correlation of this series with the description of the sense of the photospheric magnetic field is then computed. Figure 4 shows this cross-correlation as a function of the lag between the two variables. A prominent positive correlation is observed at a lag of approximately 4 1/2 days. How are we to interprete this 4 1/2 day lag? If we assume that the velocity of the solar wind is constant and radial from the sun to the earth and use the solar wind velocity observed by plasma detectors on the IMP-1 satellite, we obtain a transit time for the solar wind from the sun to the earth which is consistent with the lag of the positive peak shown in Figure 4. These results indicate that some of the photospheric magnetic field lines are dragged out by the solar wind to form a portion of the interplanetary magnetic field.

Since the interplanetary magnetic field lines have been shown to be rooted in the photosphere we would expect the interplanetary magnetic field to corotate with the sun. If we compute an autocorrelation of the function described above that describes the sense of the interplanetary magnetic field we would expect to find a large positive peak at approximately 27 days, i.e. the period of rotation of the low latitude regions on the sun as seen from the earth. The result of this autocorrelation is displayed in Figure 5. The large positive peak at about 27 days is consistent with the above discussion. Since the peak is centered at about 27 days (and not at 28 or 29 days) the latitude of the solar source of the interplanetary field appears to be near the equator[10], as can be ascertained by comparison of the rotation periods at various latitudes given in Figure 1.

A Quasi-Stationary Co-Rotating Sector Structure in the Interplanetary Magnetic Field

A longitudinal sector structure observed[12] in the interplanetary magnetic field during 3 solar rotations is shown in Figure 6. For approximately 2/7 of the total circumference the interplanetary field is almost entirely directed away from the sun, then for 2/7 of the circumference toward the sun, 2/7 away, and finally 1/7 towards the sun. This pattern corotates with the sun as discussed above so that it rotates once past the earth every 27 days. Satellite observations of the sense of the interplanetary magnetic field are indicated with plus and minus signs at the perimeter of Figure 6. The first orbit is labeled and the next orbits follow in a clockwise direction. It can be noted that the sector description at the center of the figure is a very good approximation; i.e. a sector with the field labeled away from the sun is almost entirely occupied by plus signs and similarly a sector with an arrow indicating field toward the sun is almost entirely occupied by minus signs. The second orbit appears to contain an exception in having several plus signs in a sector with field directed toward the sun, but this can be understood in terms of the solar wind velocity. At this time the solar wind velocity was considerably higher than average, which means that the sector boundary was transported to the earth too soon. During most of the observations the transit time of the solar wind from the sun to the earth was about 4 1/2 days. At this particular time in orbit 2 the transit time was only 3 days, and this difference of 1 1/2 days corresponds to the number of plus signs at the end of orbit 2. Since the sector structure corotates with the sun, an influence at earth caused by this structure is not due to the advance of a spherical front but rather to the rotational motion of the pattern past the earth.

We can now identify and discuss the second research problem of current interest, which is simply to understand the basic cause of the sectors. Although the pattern shown in Figure 6 was observed during only 3 solar rotations, an analysis of geomagnetic effects associated with the sector structure indicates that at least several parts of this pattern existed for 1 or 2 years or longer. As shown by the satellite observations at the perimeter of Figure 6 the pattern is not a random and disordered effect but on the contrary a very regular one. We have known for several years that there can be certain longitudes on the sun that are active for the production of sunspots and flares over a period of 1 or 2 years, but the pattern discussed here is a large scale regular effect occupying the entire longitudinal range on the sun. If such a sector pattern were to be quasi-stationary in equatorial latitudes then the differential rotation at higher latitudes would twist the pattern up very thoroughly after a few solar rotations. If the twisting becomes too great the magnetic fields might tend to merge together and wash out the sector pattern. Such a relaxation effect might appear as a change with time in the solar differential rotation. An investigation of this possibility is now in progress.

We can perhaps distinguish three characteristic scale lengths on the surface of the sun. The smallest that has been observed is related to the granulation pattern, which has a characteristic length of perhaps 700 km. The supergranulation pattern or chromospheric network observed by Simon and Leighton[13] has a characteristic length typically of 30,000 km. The sector structure discussed here would have a characteristic length of the order of the solar radius (700,000 km). The first two patterns are thought to be related to plasma motions on and near the surface of the sun. An explanation for the sector structure has not yet been proposed.

We proceed now to an analysis of the relation of the sector structure to the interplanetary magnetic field magnitude, the solar wind velocity and density, and geomagnetic effects. The magnitude of the interplanetary magnetic field is analysed in Figure 7. The abscissa represents the 7 3/4 days required for a 2/7 sector to rotate past the earth. The ordinate represents the average magnitude of the interplanetary field at the same relative position within a number of sectors. Sectors with field directed away from the sun and with field directed toward the sun are shown separately. The magnetic field reaches a peak early in the sector of greater than 6 γ and then declines in the trailing portion of the sector to less than 4 γ.

The discussion so far has been entirely in terms of observations of the magnetic field. It is clearly important to know whether the solar wind plasma also is organized by the sector structure. The observations of the solar wind by the MIT Faraday cup experiment[14] on IMP-1 have been analysed for this purpose. The solar wind velocity is shown in Figure 8 in a format similar to that used in Figure 7. The velocity reaches a peak near the second day of the sector and then declines in the trailing portions of the sectors. A large quantitative effect is observed in a similar analysis of the solar wind density shown in Figure 9. The density reaches a peak greater than 14 protons/cc at about the first day of the sector and then declines precipitously to less than 7 protons/cc in the middle portion of the sector, and then increases again in the trailing portions of the sector. Thus the density reaches a peak about one day before the peak of the velocity, and in the trailing portions of the sector the density is increasing while the velocity continues to decline. Since the solar wind plasma also participates in the sector structure, the structure is an important property of the interplanetary medium, and for that matter of the inner solar system.

We can now identify and discuss the third research problem of current interest which is an explanation for how the characteristic shapes of interplanetary field magnitude and solar wind velocity and density shown in Figures 7, 8 and 9 are produced. Some quasi-stationary structure in the outer layers of the sun having a longitudinal organization similar to that shown in Figure 6 would seem to be involved. What is the configuration in the photosphere, chromosphere, and lower corona that produces the particular distributions that have been observed in Figures 7, 8 and 9? Is the spiked-helmet structure sometimes observed in the lower corona of importance in this regard? Which of the 3 quantities, if any, is the most fundamental? Does a rapid increase in velocity produce a shock wave that increases the density, or is the change in density by a factor of two a direct reflection of conditions on the sun? Perhaps the sector structure should be invoked in discussions of magnetic variable stars and of acceleration processes in astrophysical contexts.

Interaction with the Geomagnetic Field

Does geomagnetic activity respond as the sector structure rotates past the earth? The answer to this question is shown in Figure 10, which shows the same analysis applied to an index of geomagnetic activity, the 24 hour sum of Kp. Geomagnetic activity reaches a peak of greater than 25 at approximately the second day of the sector and then declines to less than 10 in the trailing portions of the sector. The results for sectors with field directed away from the sun and with field directed toward the sun are shown separately in Figure 10. The degree to which the two curves have the same shape gives one a measure of the statistical reliability of the result. The large influence of the sectors on geomagnetic activity suggests the possibility that other details of the radiation belts may be strongly influenced by the sector pattern. Williams[15] has found that electrons of energy greater than 270 keV at a few earth radii are considerably influenced by the sector pattern.

We may consider briefly the interaction to be expected when the streaming magnetized solar wind encounters an obstacle such as the geomagnetic field. The solar wind plasma is supersonic, i.e. the flow velocity is much larger than the wave velocity within the plasma. Thus a collisionless shock forms which slows down the plasma so that it can then flow around the obstacle. The plasma is collisionless because the mean free path for Coulomb collisions is of the order of one astronomical unit. Nevertheless the presence of the weak interplanetary magnetic field couples the particles together and produces a fluid-like motion on a distance scale greater than the proton gyro-radius, which is measured in hundreds of kilometers. Inside the collisionless shock surface is another surface at which pressure balance occurs between the oncoming solar wind and the magnetic pressure of the compressed geomagnetic field. This latter surface is called the magnetopause. Geomagnetic lines at high latitudes are pulled by the solar wind into a long tail stretching in the anti-solar direction. This region is bisected by a neutral sheet which is approximately an extension of the plane of the geomagnetic equator. N. F. Ness[16] has discovered and elucidated many of these phenomena, and discusses them in a companion paper in this volume.

Terrestial Plasmas

We may now descend to earth and land in a plasma laboratory, such as that of H. Alfvén in Stockholm, which the author has recently visited. Several laboratories in various parts of the world are attempting to simulate the interaction between the geomagnetic field and the solar wind with laboratory plasma experiments.[17-19] The experiment of Danielsson and Lindberg[20] in Stockholm is representative of these efforts. Plasma is accelerated in a coaxial gun and approaches a terrella, the latter being a small sphere with a dipole field which represents the earth. In the case shown in Figure 11 the magnetic field frozen into the streaming plasma is parallel to the external field of the terrella in equatorial regions. The plasma flow is from left to right and the axis of the terrella is in the vertical direction. A spherical front can be distinguished at the boundary between the streaming plasma and the terrella field. Figure 12 shows the same situation except that the terrella field is reversed, such that it is now anti-parallel to the field frozen into the streaming plasma. This case has been discussed by Dungey[21], who predicts that a X-type singularity will be formed. Such a singularity can be distinguished in Figure 12. Probe measurements indicate that the flow of the plasma is towards the X on both sides of it, as predicted by Dungey. As yet the laboratory experiments do not show the collisionless shock or the neutral sheet discussed above that are found in the geophysical case. One reason for this is the difficulty of preparing a suitably hot and tenuous streaming plasma. This difficulty also exists in the laboratory experiments attempting to produce controlled thermonuclear fusion.

There has been a considerable interaction between astrophysics and the efforts toward controlled thermonuclear reactions. The early ideas of Alfvén[22] on hydromagnetic waves and on the first adiabatic invariant that came from his investigations in astrophysics have been basic to the attempts toward controlled thermonuclear reactions. On the other hand numerous instabilities observed in the laboratory experiments have been invoked in astrophysics. One sticky problem in discussions of the sun is that of time scales. The changes in the photospheric field discussed above occurring in times of a few days or a few solar rotations would not be allowed by simple diffusion of magnetic lines through the plasma. The solar magnetic field is an attractive energy source for solar flares, but the release of the energy within a few minutes poses a difficult theoretical problem. A number of the instabilities observed in the laboratory have been invoked at various times in attempts to explain the fast time scales observed on the sun. At the International Astronomical Union Symposium on Solar and Stellar Magnetic Fields in 1963, Cowling[23] had, the following comment on these efforts: "We find ourselves in these days tempted regularly to invoke motions across the lines of force. Well, such motions are met with in certain circumstances, and we have to reckon with them. But I think one should regard it as the last confession of weakness rather than the first straw to be clutched at." Of course this may perhaps just be an example of Alfvén's theorem: "Given Cowling, there can be no theoretical astrophysics."

Acknowledgements

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Figure Legends

Fig. 1. Solar magnetic field regions for the sunspot cycle that ended in 1964. A pair of sunspots is surrounded by a Bipolar Magnetic Region (BMR). Solid contours indicate magnetic field out of the sun and dashed contours indicate magnetic field into the sun. The large region with field into the sun is a Unipolar Magnetic Region (UMR). Field polarities in the southern hemisphere are opposite that in the northern hemisphere. When the sun is observed with fine scale resolution the indicated contours usually contain small areas of oppositely-directed field. The synodic rotation periods at various latitudes are indicated. For quantitative analysis a strip at a given latitude is divided into small areas as shown here and discussed in the text.

Fig. 2. Synoptic chart of the photospheric magnetic field. Solid contours represent field directed out of the sun and dashed contours represent field directed into the sun. Contour levels are 2, 4, 8, 12 and 25 gauss.

Fig. 3. Distribution of the interplanetary magnetic field directions parallel and normal to the ecliptic averaged over 3 hour intervals, as measured with the IMP-1 satellite. Both histograms show the field angular distribution per unit solid angle; the dashed circles would correspond to an isotropic distribution of the same number of vectors. The distribution is peaked in directions corresponding to the spiral streaming angle. The angular intervals in which the field is predominantly away from the sun and predominantly toward the sun are labeled positive and negative in this figure, and represented by + and - signs in Figure 6. The distribution normal to the ecliptic shows that the interplanetary field is predominantly parallel to the ecliptic rather than

Fig. 4. Crosscorrelation as a function of time lag of the sense of the nearby interplanetary magnetic field and the sense of the photospheric magnetic field for solar latitudes at the center of the visible disk and at 5^{O}N thereof.

Fig. 5. Autocorrelation of the sense of the nearby interplanetary magnetic field observed with the IMP-1 satellite. The prominent positive peak at about 27 days is consistent with the corotation of the interplanetary magnetic field with the sun. The dashed line is related to the sector structure shown in Figure 6.

Fig. 6. The + (away from the sun) and - (towards the sun) signs at the circumference of the figure indicate the direction of the measured interplanetary magnetic field during successive 3 hour intervals. A parenthesis around a + or - indicates a time during which the field direction has moved beyond the "allowed regions" shown in Figure 3 for a few hours in a smooth and continuous manner. The inner portion of the figure is a schematic representation of a sector structure of the interplanetary magnetic field that is suggested by these observations. The deviations about the average streaming angle that are actually present are not shown in this figure.

Fig. 7. Superposed epoch analysis of the magnitude of the interplanetary magnetic field as a function of position within the 2/7 sectors shown in Figure 6. The abscissa represents position within the sector, measured in days as the sector sweeps past the earth. The ordinate is the average magnitude at the same relative position within the sectors. The results are shown separately for the sectors with field away from the sun, the sectors with field toward the sun, and for all sectors.

Fig. 8. Superposed epoch analysis of the solar wind velocity as a function of position within the 2/7 sectors.

Fig. 9. Superposed epoch analysis of the solar wind density as a function of position within the 2/7 sectors.

Fig. 10. Superposed epoch analysis of the geomagnetic activity index 24 hour sum Kp as a function of position within the 2/7 sectors.

Fig. 11. Laboratory simulation[20] of the interaction between the solar wind and the geomagnetic field. The sphere in the center of the figure represents the earth and has a magnetic dipole in the vertical direction. A streaming plasma approaches from the left with a frozen-in field parallel to the dipole field that it encounters. A sphere of interaction can be distinguished.

Fig. 12. Same as Figure 11, except that the frozen-in field in the streaming plasma is anti-parallel to the dipole field. The interaction surface now appears to be similar to the X-type singularity predicted by Dungey.[21]

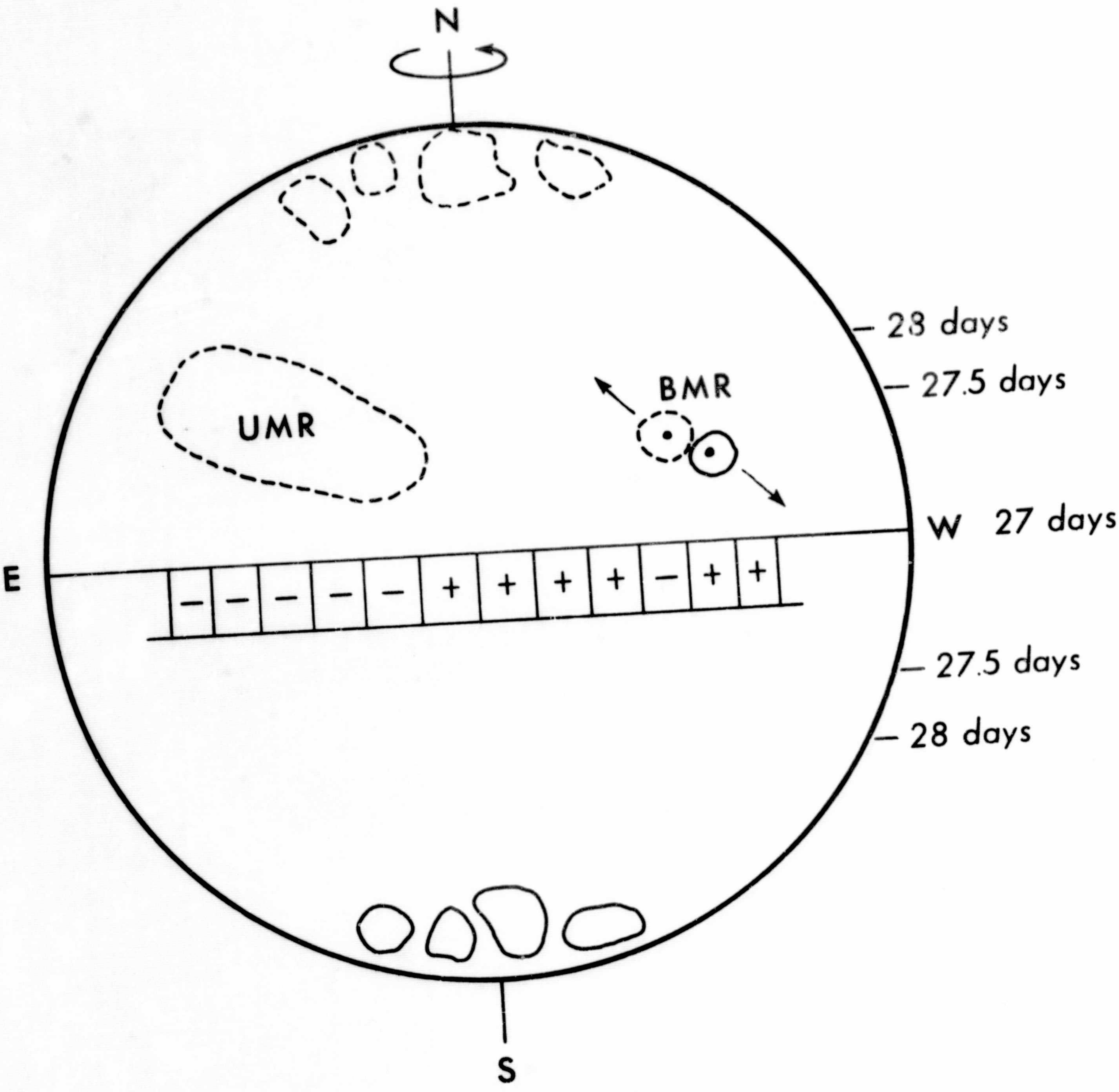
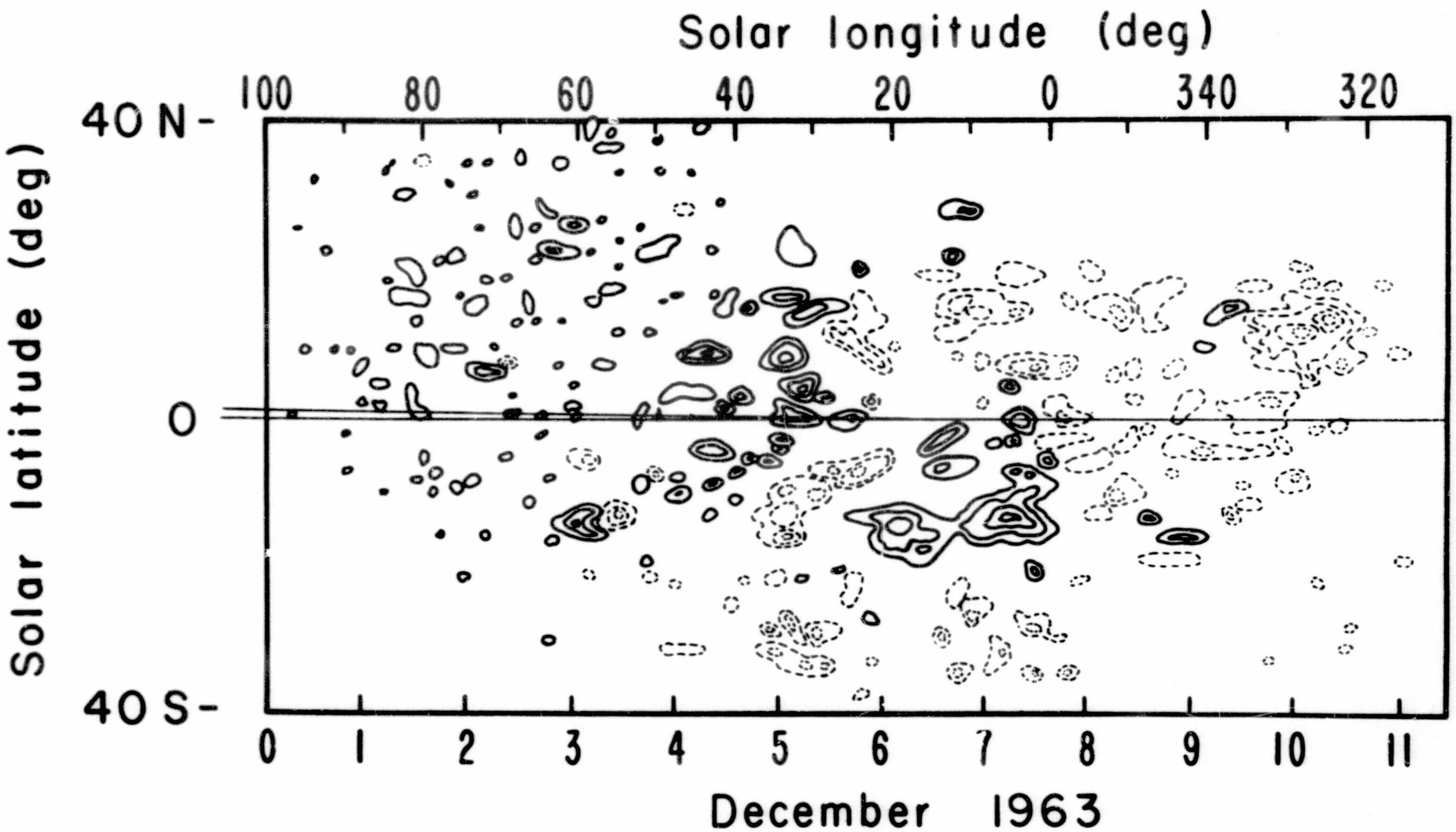
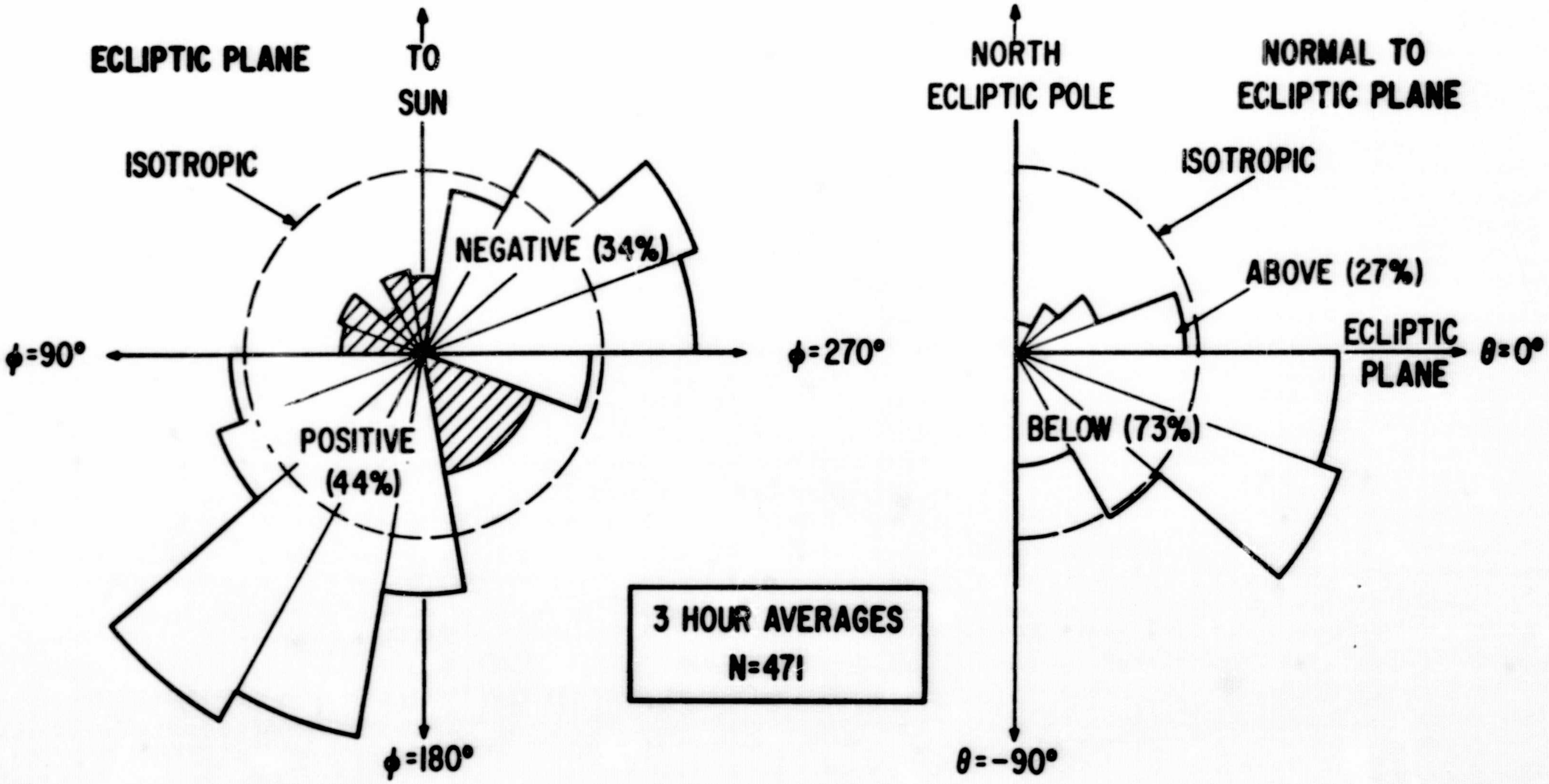


FIGURE 1



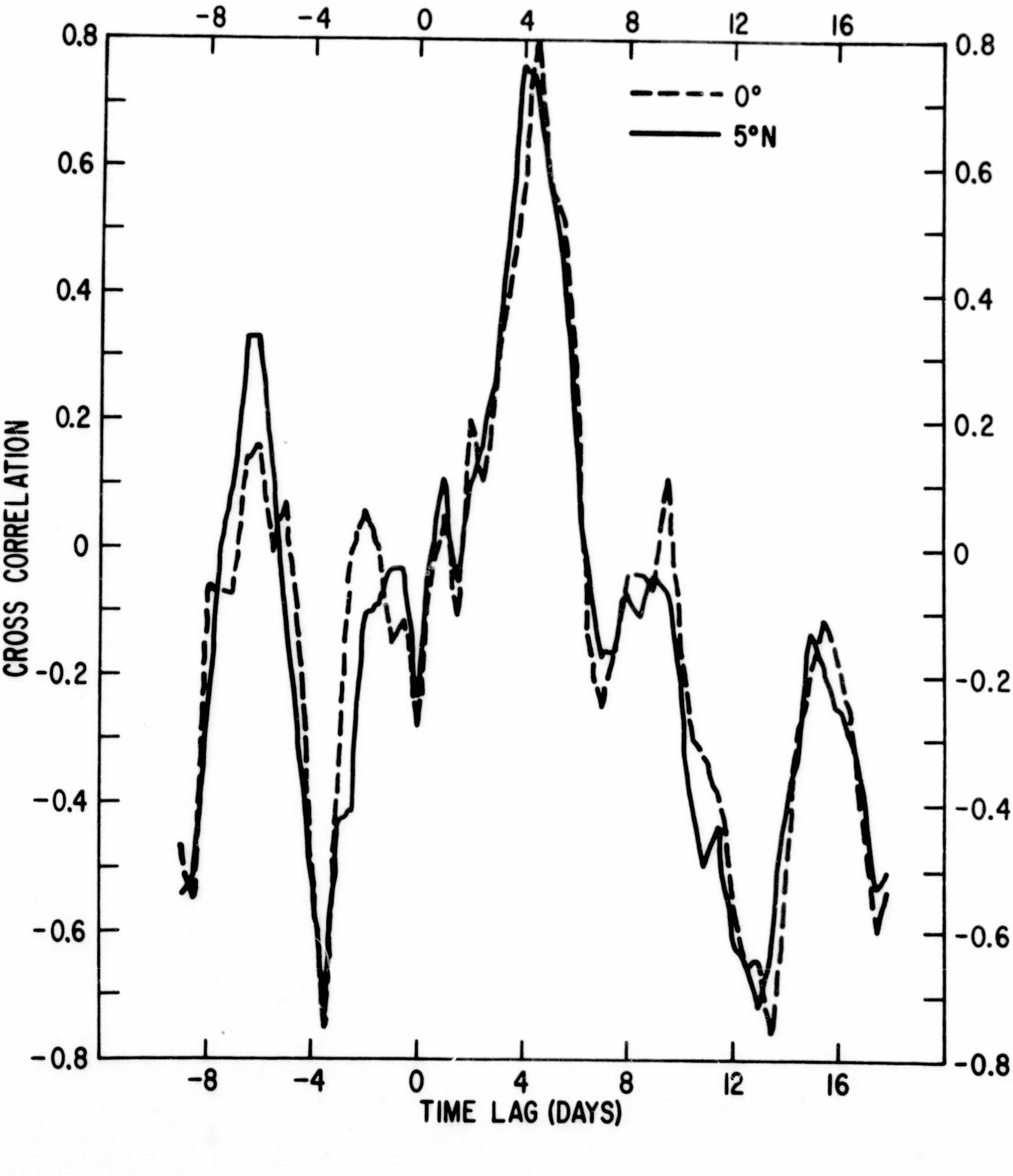
Solar longitude (deg)
100
80
60
40
20
0
340
320
40 N-
0
40 S-
Solar latitude (deg)
0
1
2
3
4
5
6
7
8
9
10
11
December 1963

FIGURE 2



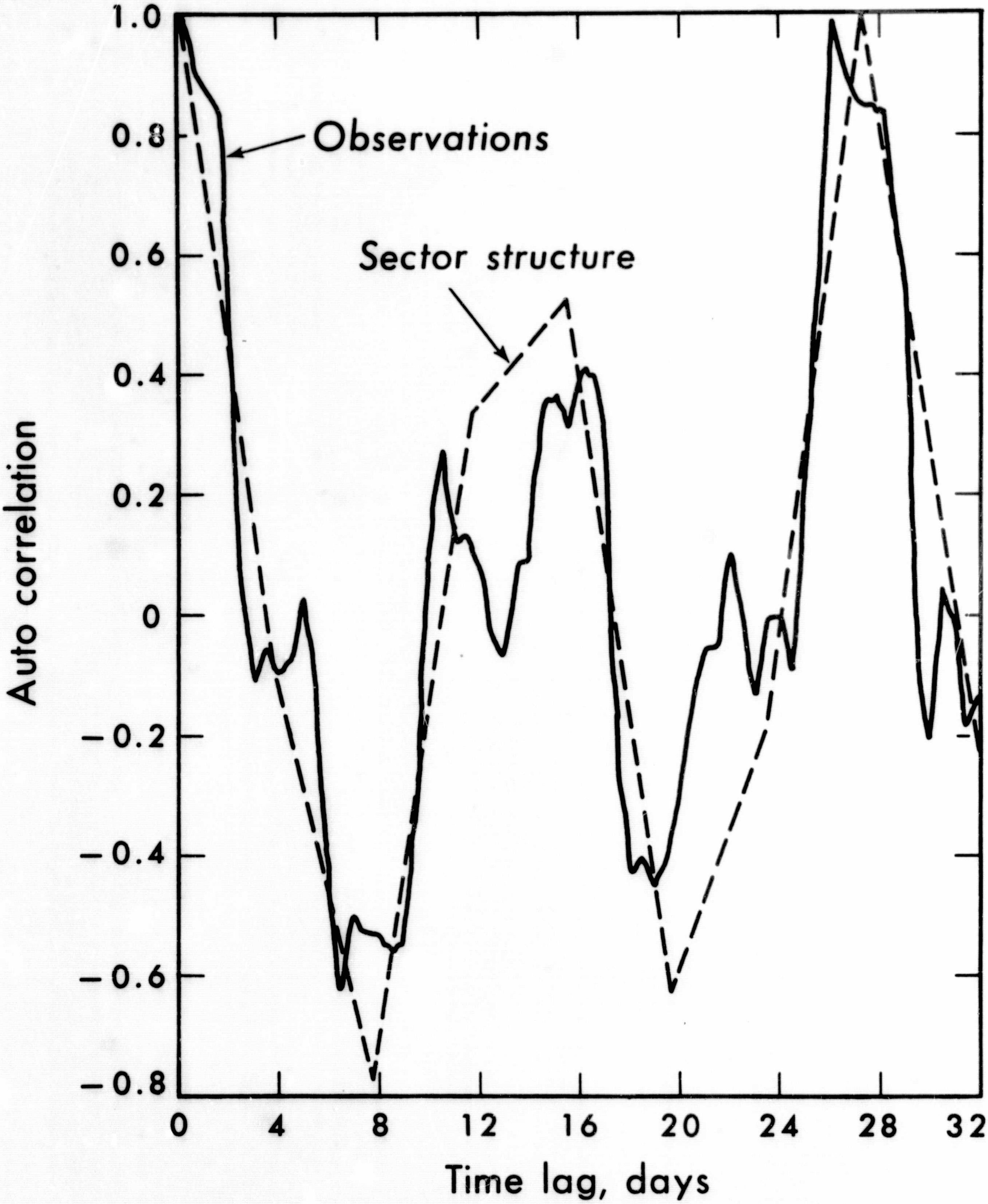
DISTRIBUTION OF INTERPLANETARY MAGNETIC FIELD DIRECTION

FIGURE 3



-8
-4
0
4
8
12
16
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
0°
5°N
CROSS CORRELATION
TIME LAG (DAYS)

FIGURE 4



Auto correlation
1.0
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
Observations
Sector structure
0
4
8
12
16
20
24
28
32
Time lag, days

FIGURE 5

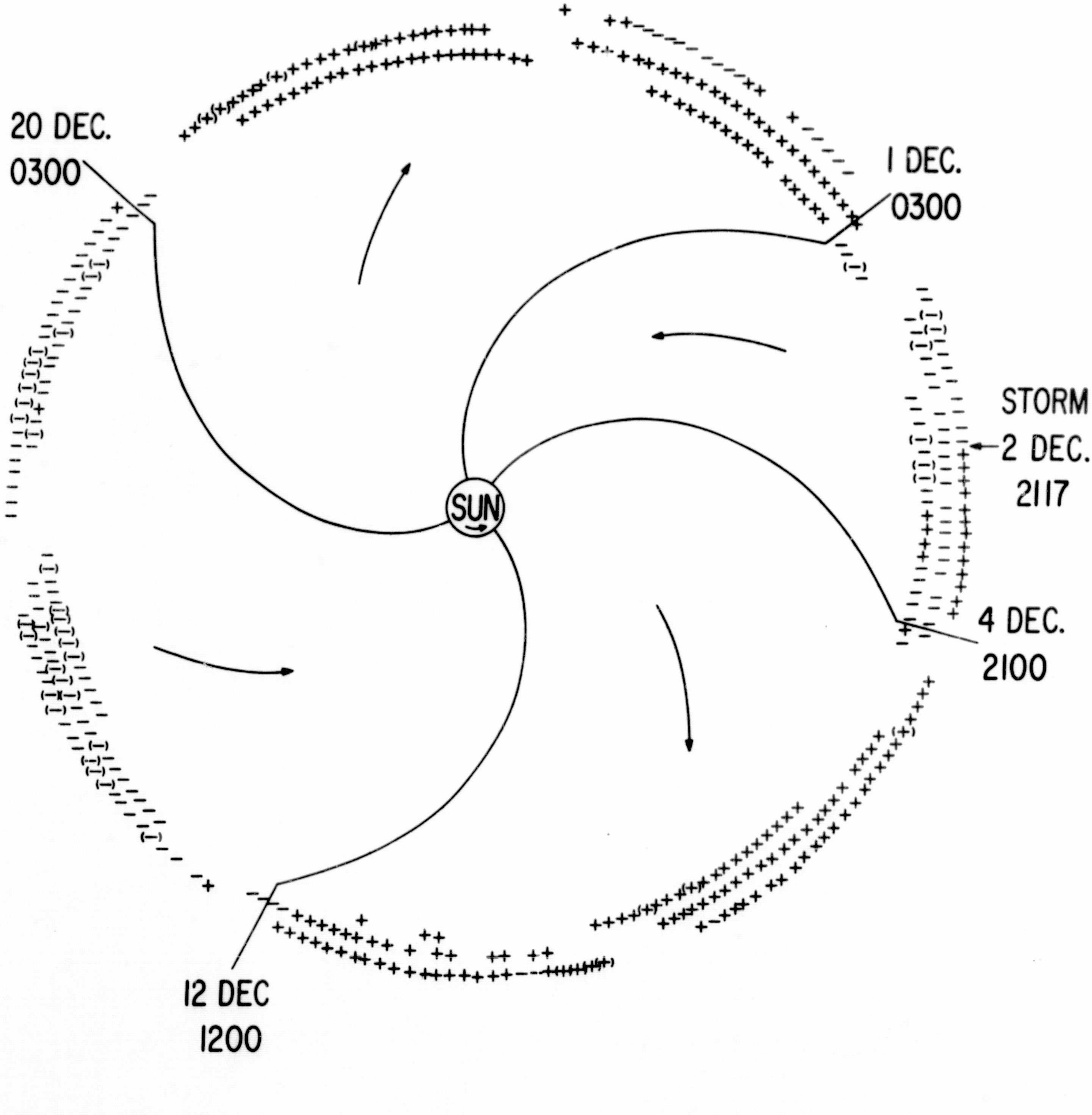

20 DEC.
0300
1 DEC.
0300
STORM
2 DEC.
2117
4 DEC.
2100
12 DEC
1200
SUN

FIGURE 6

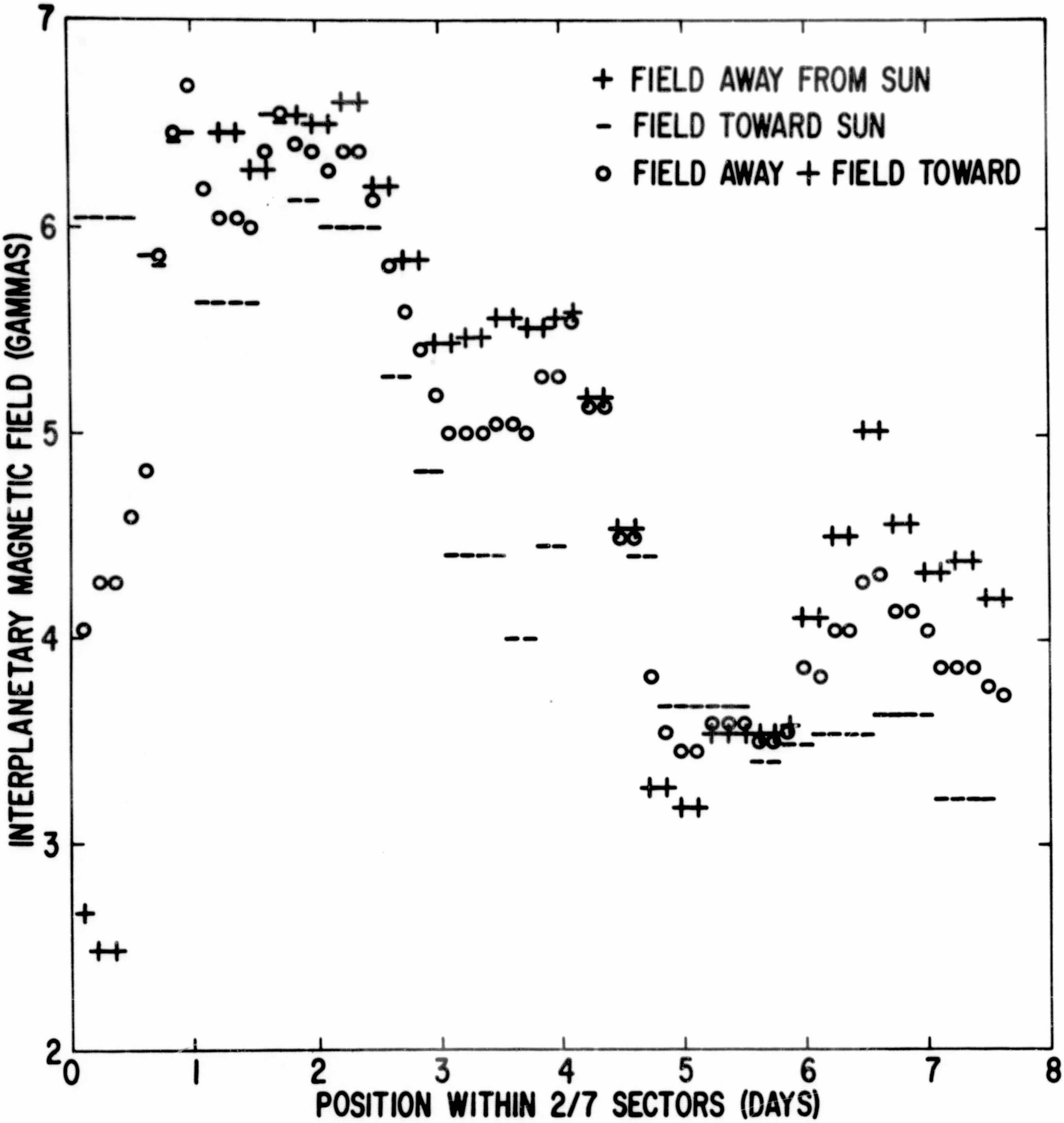
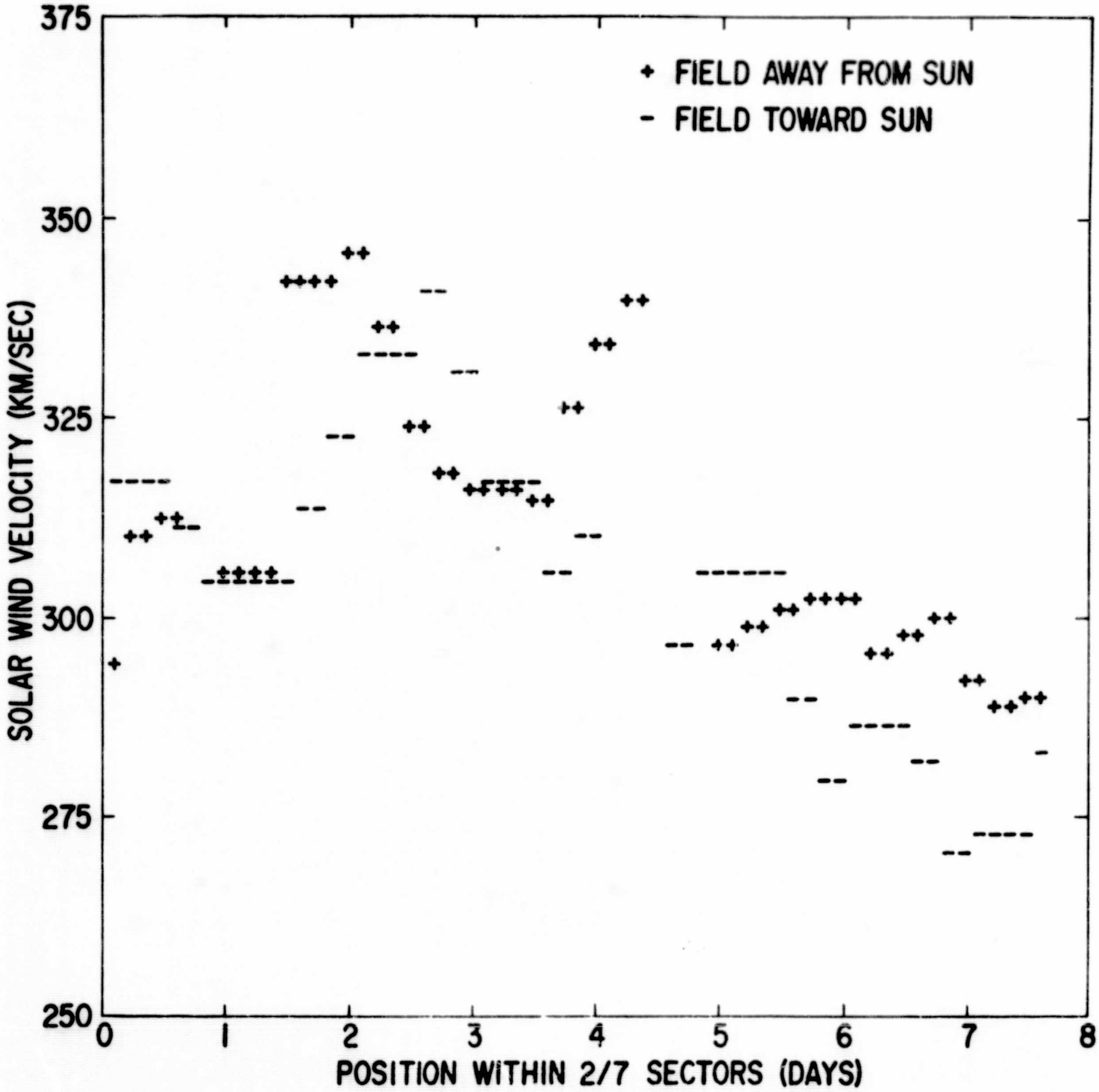
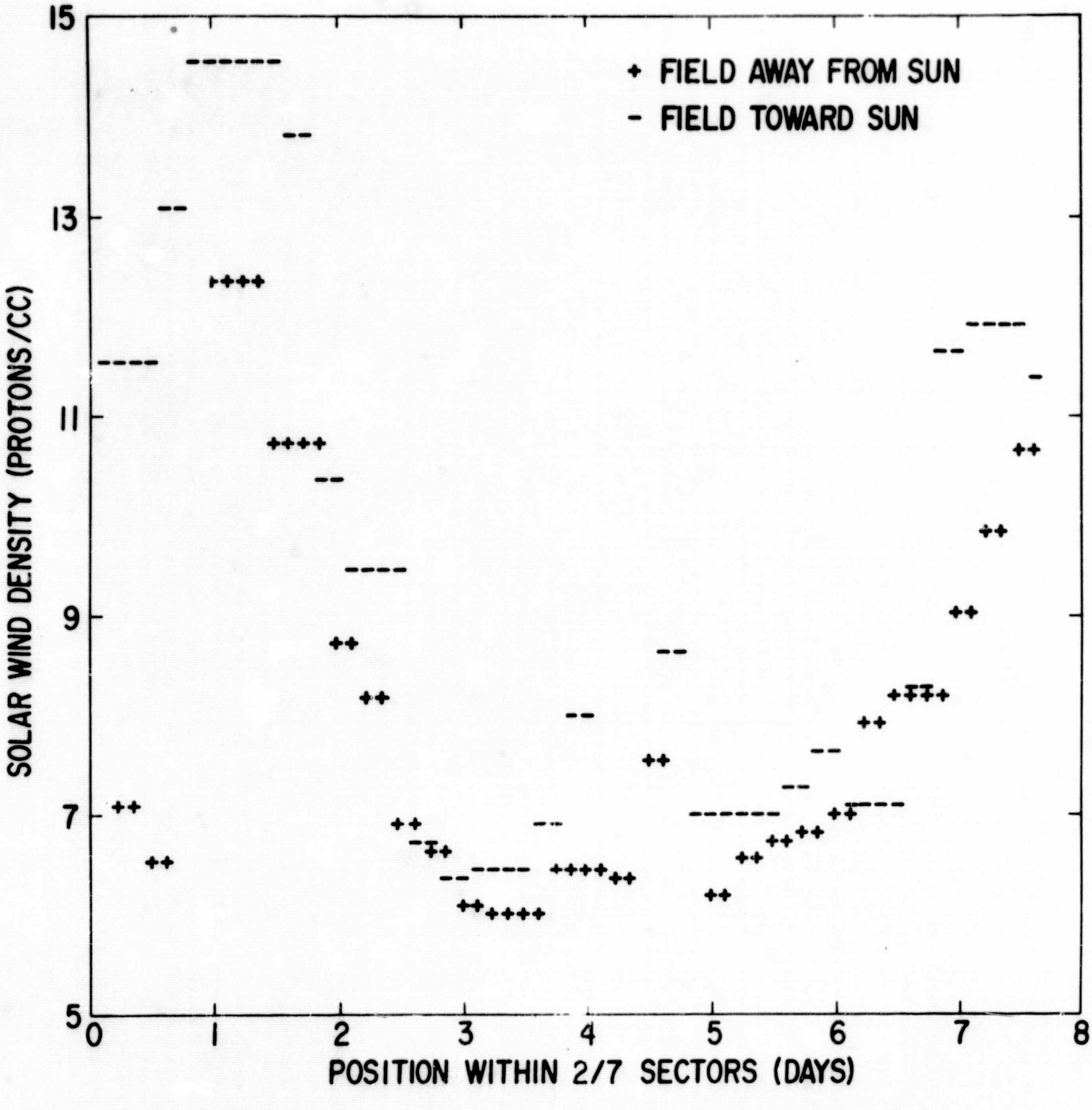

+ FIELD AWAY FROM SUN
- FIELD TOWARD SUN
o FIELD AWAY + FIELD TOWARD
INTERPLANETARY MAGNETIC FIELD (GAMMAS)
POSITION WITHIN 2/7 SECTORS (DAYS)
2
3
4
5
6
7
0
1
2
3
4
5
6
7
8

FIGURE 7



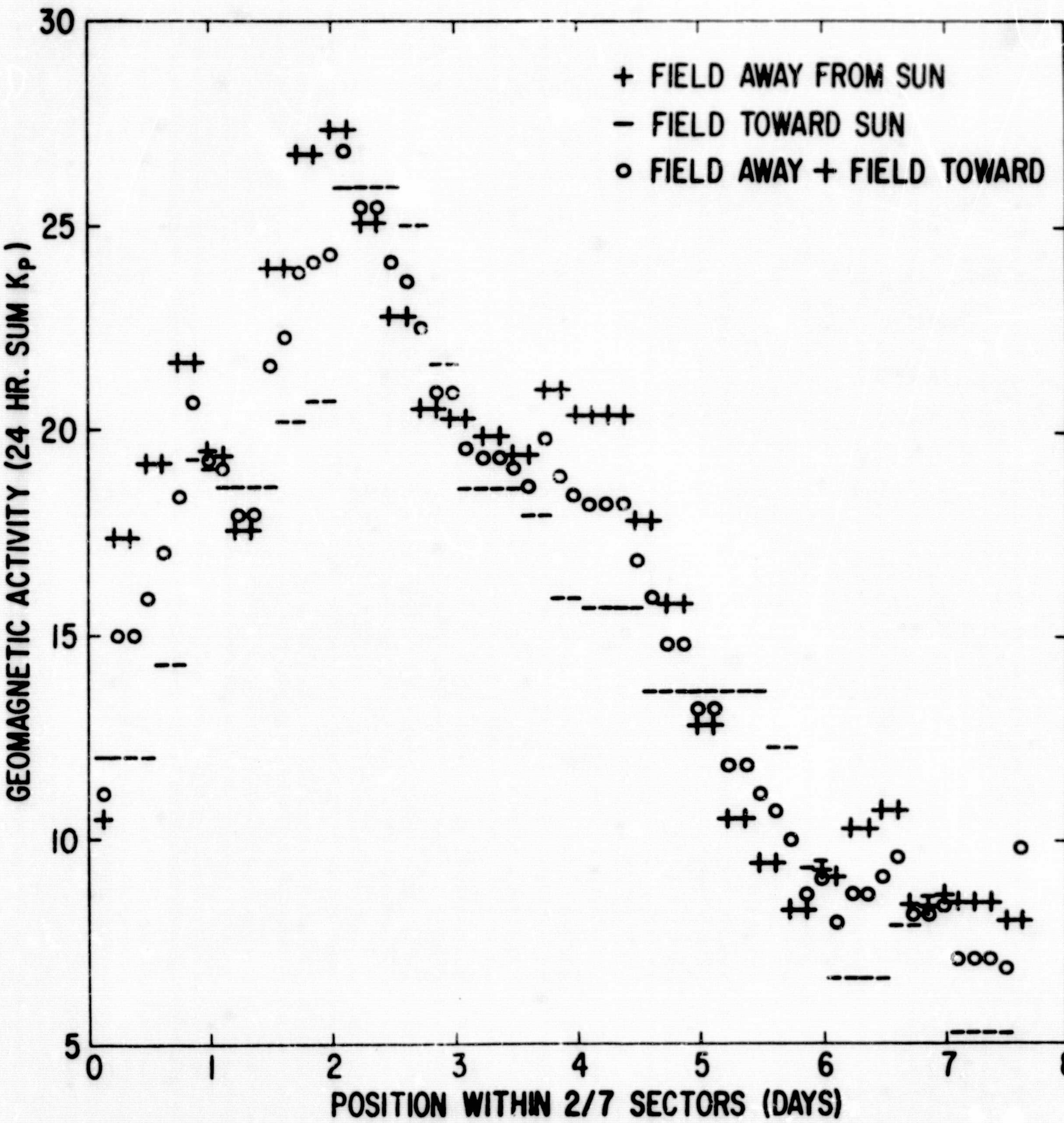
375
350
325
300
275
250
0
1
2
3
4
5
6
7
8
+ FIELD AWAY FROM SUN
- FIELD TOWARD SUN
SOLAR WIND VELOCITY (KM/SEC)
POSITION WITHIN 2/7 SECTORS (DAYS)

FIGURE 8



15
13
11
9
7
5
0
1
2
3
4
5
6
7
8
+ FIELD AWAY FROM SUN
- FIELD TOWARD SUN
SOLAR WIND DENSITY (PROTONS/CC)
POSITION WITHIN 2/7 SECTORS (DAYS)

FIGURE 9



+ FIELD AWAY FROM SUN
− FIELD TOWARD SUN
o FIELD AWAY + FIELD TOWARD
GEOMAGNETIC ACTIVITY (24 HR. SUM K_p)
30
25
20
15
10
5
0
1
2
3
4
5
6
7
8
POSITION WITHIN 2/7 SECTORS (DAYS)

FIGURE 10

FIGURE 11

FIGURE 12